

Large-Amplitude Internal Waves in the South China Sea

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Prologue: One of the most spectacular phenomena recently discovered in the South China Sea is that of very large internal waves. Field observations and satellite images show that these internal waves are over 200 meters in amplitude and their crests extend more than 200 km (Fig. 3). These fast, transient, large-amplitude internal waves can push water up or down 200 meters in 10 minutes and seriously impact the safe operation of submerged vessels, particularly the less powerful unmanned undersea vessels, or UUVs. The large-amplitude internal waves can also have a strong effect on underwater sound propagation as reported by the Office of Naval Research (ONR) Asian Seas International Acoustics Experiment.¹ Several NRL scientists from the Acoustics and Oceanography Divisions participated in this experiment. In 2005, ONR launched the Nonlinear Internal Waves Initiative (NLIWI) to better understand the large-amplitude internal waves in the South China Sea. NRL teamed with university scientists to participate in the NLIWI to conduct internal wave studies using computer ocean models and observations.

Modeling Tools: We used a hydrostatic ocean model for the northern South China Sea and non-hydrostatic, process-oriented ocean models to study the large-amplitude internal waves. The hydrostatic model is the NRL Ocean Nowcast/Forecast System (ONFS).² The NRL ONFS was implemented using a nested grid system. The larger grid covers the East Asian Seas and provides boundary conditions for a higher-resolution grid that includes the Luzon Strait and northern South China Sea (Fig. 3). Tidal forcing is applied at the open boundary of the high-resolution grid. Temperature and salinity analyses generated from satellite altimeter and Multi-Channel Sea Surface Temperature (MCSST) data are assimilated into the model to produce a realistic stratification. Applying the NRL ONFS and non-hydrostatic models, numerical experiments were conducted and analyses were made to study the effects of bottom topography, tidal forcing, and stratification on the generation and propagation of the large-amplitude internal waves.

How Large-Amplitude Internal Waves are Generated: Figure 4 illustrates how the undersea ridges in

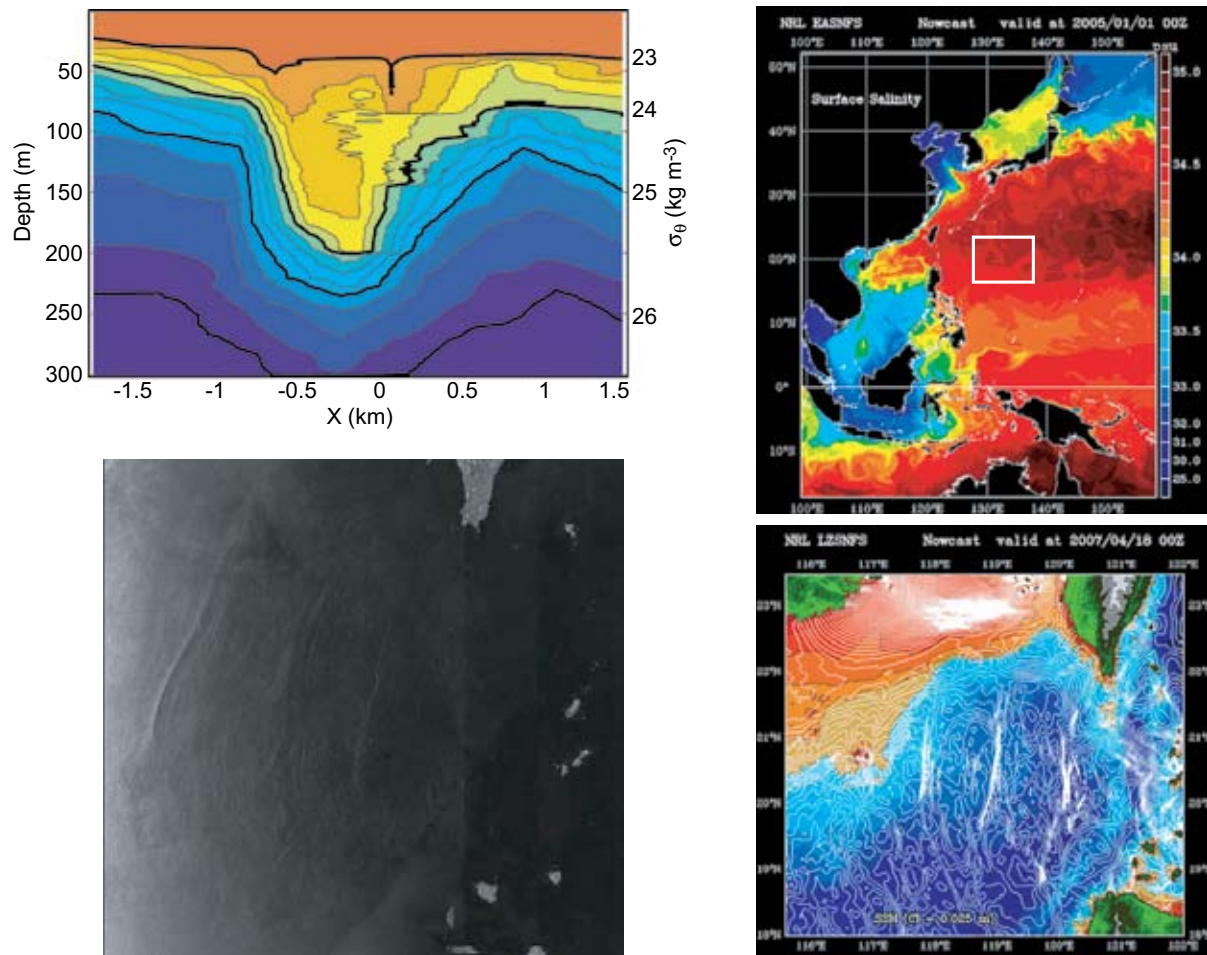
the Luzon Strait transform the ocean tide into large-amplitude internal waves. Large amounts of water rush through the Luzon Strait pushed by the tide. The ridges first convert the barotropic tides to internal tides. Propagating away from the ridges, the internal tidal wave steepens, and transforms the internal tide to an internal bore. The internal bore evolves into a large-amplitude, internal solitary wave as it propagates further away from the ridges. If the tide is strong, the solitary wave may develop into a packet of internal solitary waves.

Where is the Source? The east ridge in the middle reaches of the Luzon Strait is the major internal wave generation site where the internal tidal energy flux diverges (Fig. 4). There is a secondary generation site at the northern shallow reaches of the west ridge south of Taiwan. The internal tidal energy generated at these two locations propagates westward into the deep northern South China Sea and dissipates on the shallow shelf. The west ridge in the middle portion of the Luzon Strait blocks part of the incoming internal tidal energy from the east ridge.³

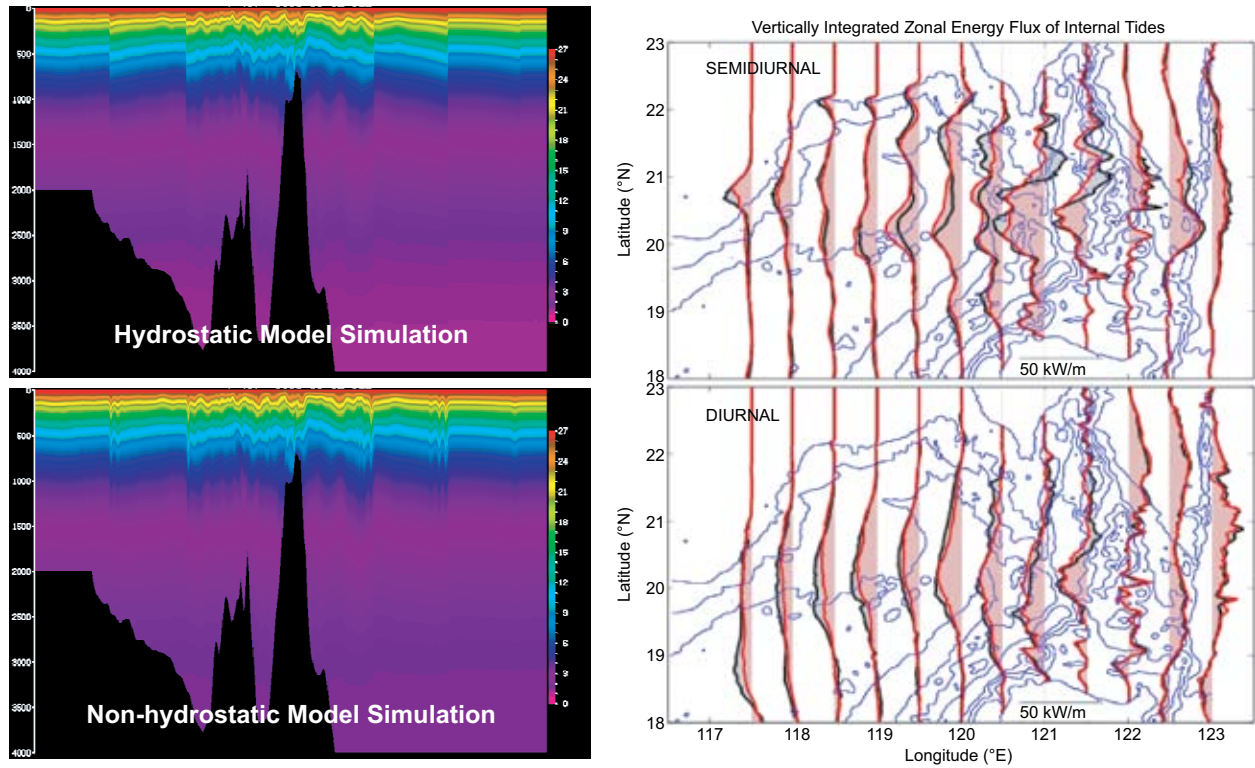
Which Tide Generates the Internal Waves? The barotropic tides are the major forcing that generates internal waves in the South China Sea. Without the tide, internal energy can be generated by the frontal instability of the Kuroshio current or by Kuroshio-topography interaction, but this energy is much weaker than the internal energy produced by the tides. The semidiurnal tide is more effective than the diurnal tide in generating the large-amplitude internal waves (Fig. 5). Although the strength of the semidiurnal and diurnal tides are about equal in the South China Sea, the internal tides generated by the semidiurnal tides have a shorter wave length and more easily evolve into large-amplitude internal waves. Concurrent satellite synthetic aperture radar (SAR) images and shipboard observations suggest that this is the case.

Can We Predict Large-Amplitude Internal Waves? The model predictability of the large-amplitude internal waves in the South China Sea was validated by field observations and satellite remote sensing data. NLIWI field observations taken during the 2005, 2006, and 2007 cruises and at three moorings during 2007 were used. The satellite SAR and Moderate Resolution Imaging Spectroradiometer (MODIS) images of 2005 were also used. The validation suggests that the timing and relative amplitude of the large-amplitude internal waves in the South China Sea can be predicted accurately (Fig. 5). The results of this study were presented to the Naval Oceanographic Office. NRL is now in the process of transitioning an internal wave prediction capability for operational application.

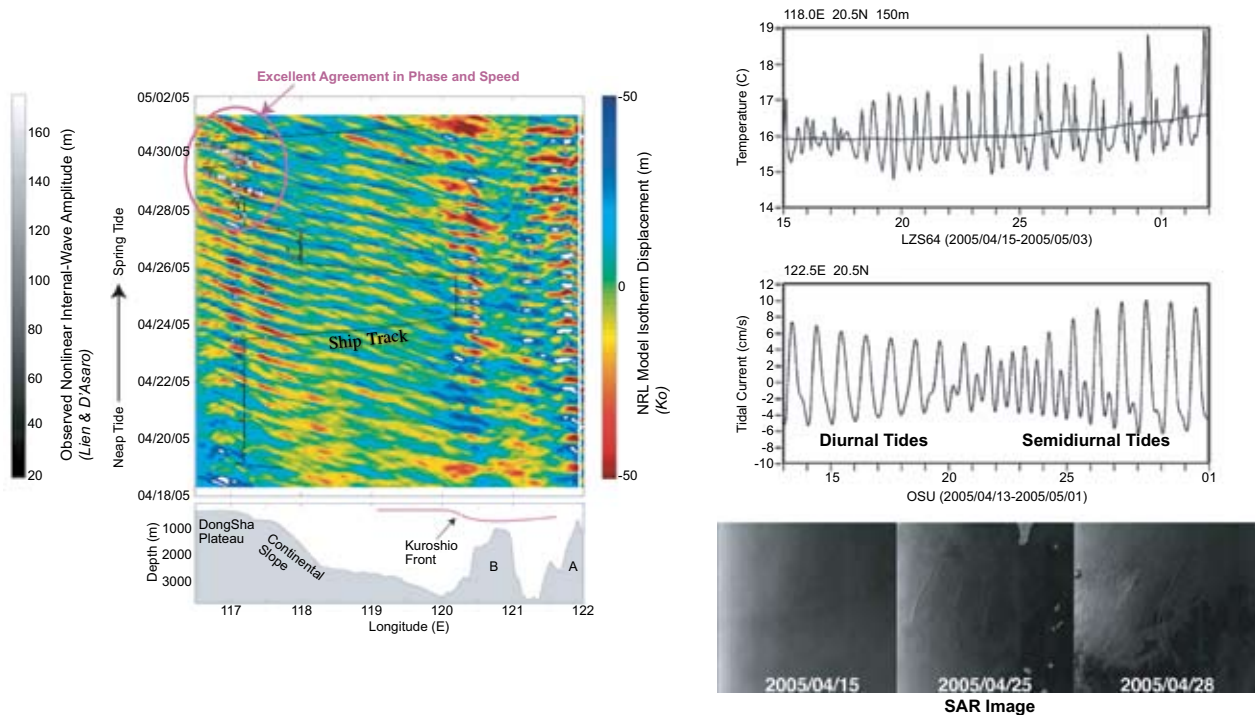
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**FIGURE 3**

Internal waves in the South China Sea have amplitudes over 200 m (top left) and extend over 200 km (bottom left). A coupled NRL Ocean Nowcast/Forecast System with a nested grid (right) is used to study the internal waves.

**FIGURE 4**

Simulations of the internal-wave generation and propagation with hydrostatic and non-hydrostatic models (left). The energy flux of the internal tides (right); red and black correspond to results with and without west ridge blocking, respectively.

**FIGURE 5**

Comparison of predicted internal waves with shipboard observations (left). Comparison of model-predicted internal waves with corresponding tidal current and satellite synthetic aperture radar (SAR) images (right).

References

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